Discovery of the Σ_b Baryons at CDF

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Featured Student Talk

Outline

- Motivation: why study heavy baryons?
- Heavy baryon spectroscopy
- Σ_b theoretical predictions
- Σ_b search methodology
- Σ_b reconstruction
- Σ_b results

Motivation

- Why study baryons with heavy quarks?
  - High energy data gives precise tests of perturbative Quantum Chromodynamics (QCD)
  - Few tests at low energies (non-perturbative)
  - Non-perturbative QCD effects could obscure or confuse new physics signatures!
  - Quark interactions inside hadrons described by non-perturbative QCD…
- Heavy baryons: best way to study non-perturbative QCD
  - Find as many states as possible
  - Measure properties (mass, width, lifetime…)
  - Compare to a number of theoretical models
- Finding new particles also good “practice” for LHC!

Heavy Baryon Spectroscopy

- Heavy quark effective theory (HQET)
  - Baryons with one heavy and two light quarks:
    - Treat heavy quark as static source of color field
    - Light quarks form a diquark pair
    - Infinite heavy quark mass → angular momentum and flavor of diquark are good quantum numbers
- HQET extensively tested for *Qq* systems, interesting to test for *Qqq*
- Heavy baryon predictions from many different models:
  - HQET, potential models, $1/N_c$ expansion, sum rules, lattice QCD

Σ_b Theoretical Predictions

- Λ_b (*udb*) lowest mass *b* baryon
  - Only established *b* baryon
  - Flavor antisymmetric diquark state
  - Decays weakly
- Enough statistics at Tevatron to probe other *b* baryons
- Σ_b next accessible baryons:
  - Flavor symmetric diquark state
  - Decays strongly

$$\Sigma_b: \{qq\}b,\ q = u,d;\ J^P = S_Q + S_{qq} \begin{cases} = 3/2^+\ (\Sigma_b^*) \\ = 1/2^+\ (\Sigma_b) \end{cases}$$

- $\Sigma_b^{(*)0}$ decay to $\Lambda_b \pi^0$
  - CDF detector can't reconstruct π^0, won't see $\Sigma_b^{(*)0}$
- $\Sigma_b^{(*)\pm}$ decay to $\Lambda_b \pi^\pm$
- We expect to see:

Σ_b^+, Σ_b^-, Σ_b^{*+}, Σ_b^{*-}

$$\boxed{\begin{aligned} \Sigma_b^{(*)0} &= udb \\ \Sigma_b^{(*)+} &= uub \\ \Sigma_b^{(*)-} &= ddb \end{aligned}}$$

Σ_b Theoretical Predictions

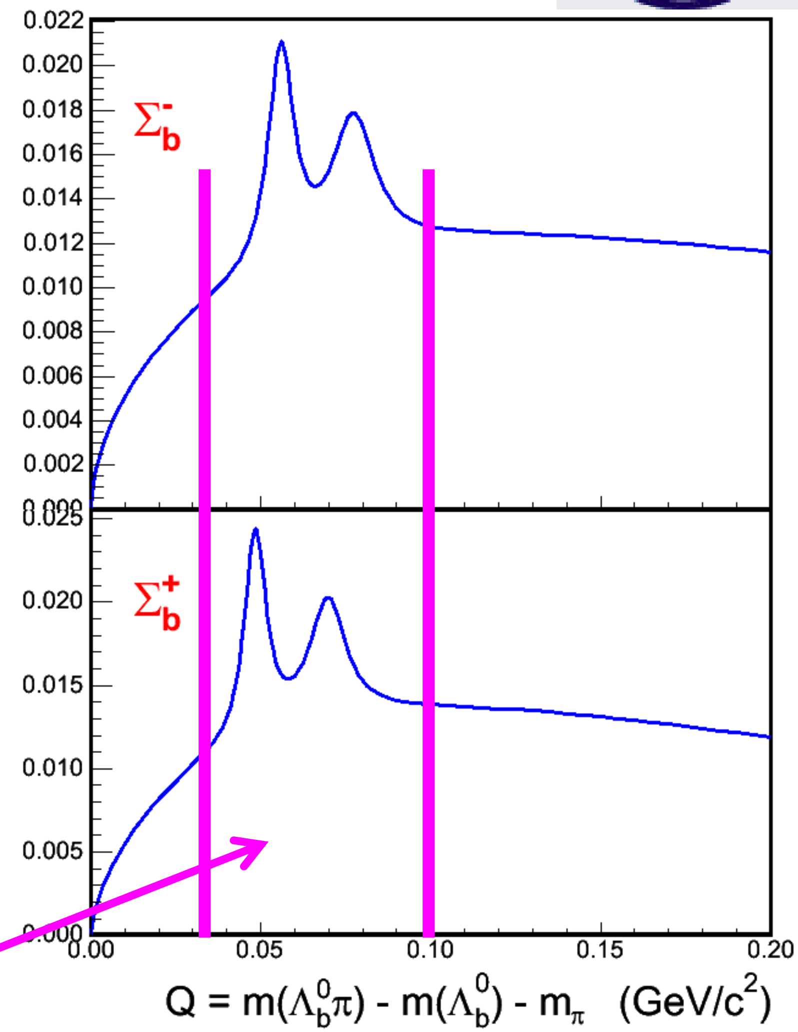
- From heavy baryon models, we expect:
  - Σ_b^* heavier than Σ_b (hyperfine splitting)
  - Σ_b^- heavier than Σ_b^+ (strong isospin splitting)
  - $\Sigma_b^{(*)}$ intrinsic width determined by phase space of one pion P-wave transition
- Summary of predictions:

Σ_b property	Expected values (MeV/c^2)
$m(\Sigma_b)$ - $m(\Lambda_b^0)$	180 – 210
$m(\Sigma_b^*)$ - $m(\Sigma_b)$	10 – 40
$m(\Sigma_b^-)$ - $m(\Sigma_b^+)$	5 – 7
$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim$8, $\sim$15

Σ_b Search Methodology

- Σ_b decays strongly at primary vertex → combine Λ_b candidate with good-quality prompt track to make Σ_b candidate
- Separate Σ_b^- and Σ_b^+:
  - $\Sigma_b^{(*)-} \to \Lambda_b^0 \pi^- \to \Lambda_c^+ \pi^- \pi^-$ (+ c.c.)
  - $\Sigma_b^{(*)+} \to \Lambda_b^0 \pi^+ \to \Lambda_c^+ \pi^- \pi^+$ (+ c.c.)
- Search for resonances in the mass difference:

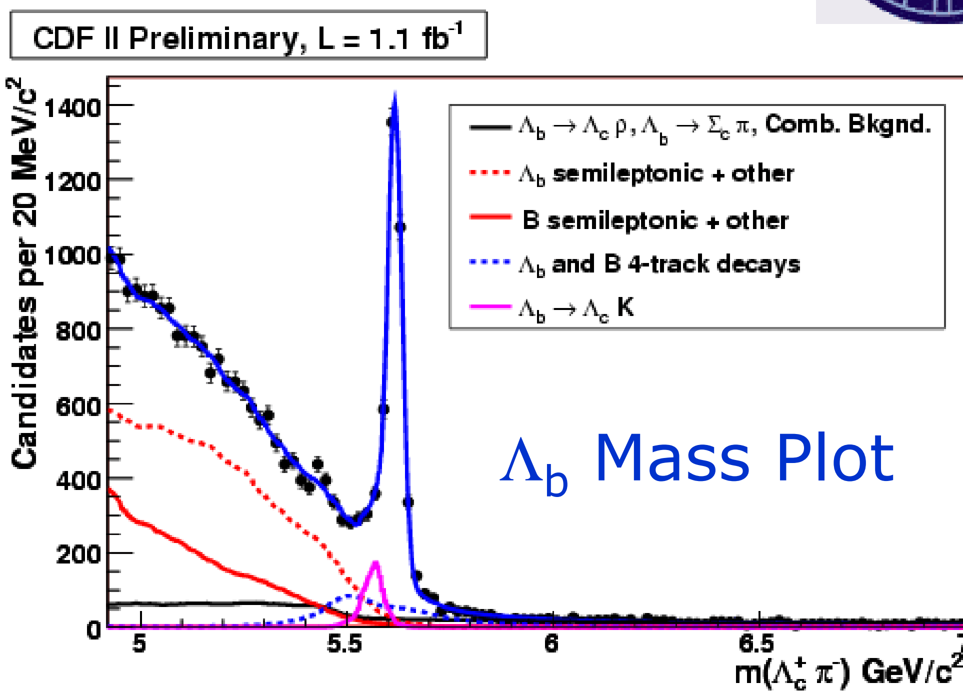
  $Q = m(\Lambda_b \pi) - m(\Lambda_b) - m_\pi$
- Unbiased Σ_b selection
  - Optimize Σ_b cuts without looking in Σ_b signal region of: $30 < Q < 100$ MeV/c^2

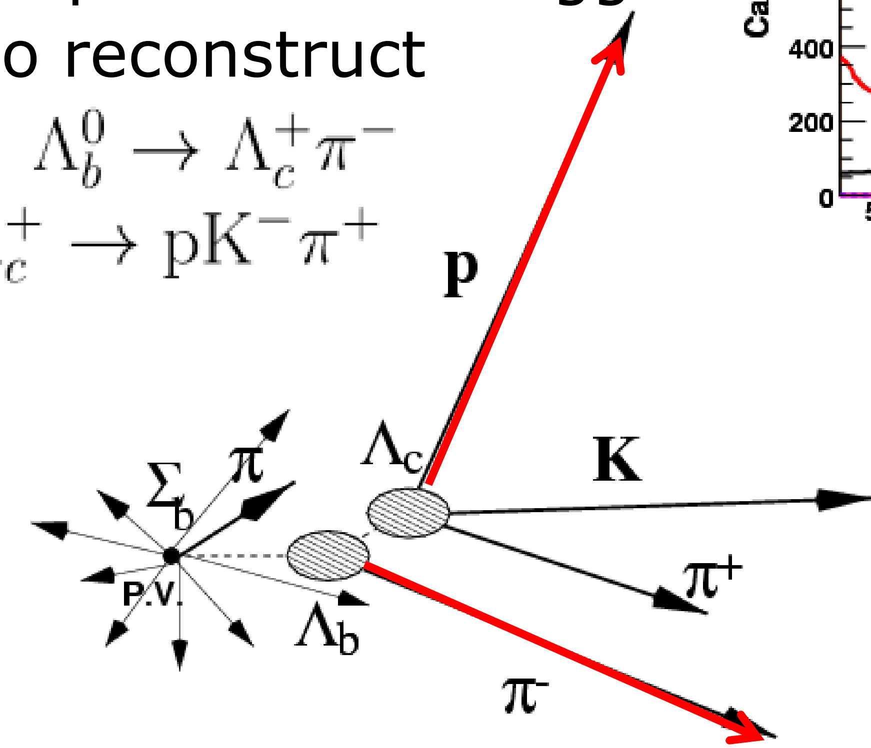


Reconstructing $\Sigma_b \rightarrow \Lambda_b \pi^{\pm}$

- In 1.1 fb^{-1} of data, CDF has world's largest sample of Λ_b: ~3000
- Use CDF's two displaced track trigger to reconstruct

$$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$$
$$\Lambda_c^+ \rightarrow pK^- \pi^+$$

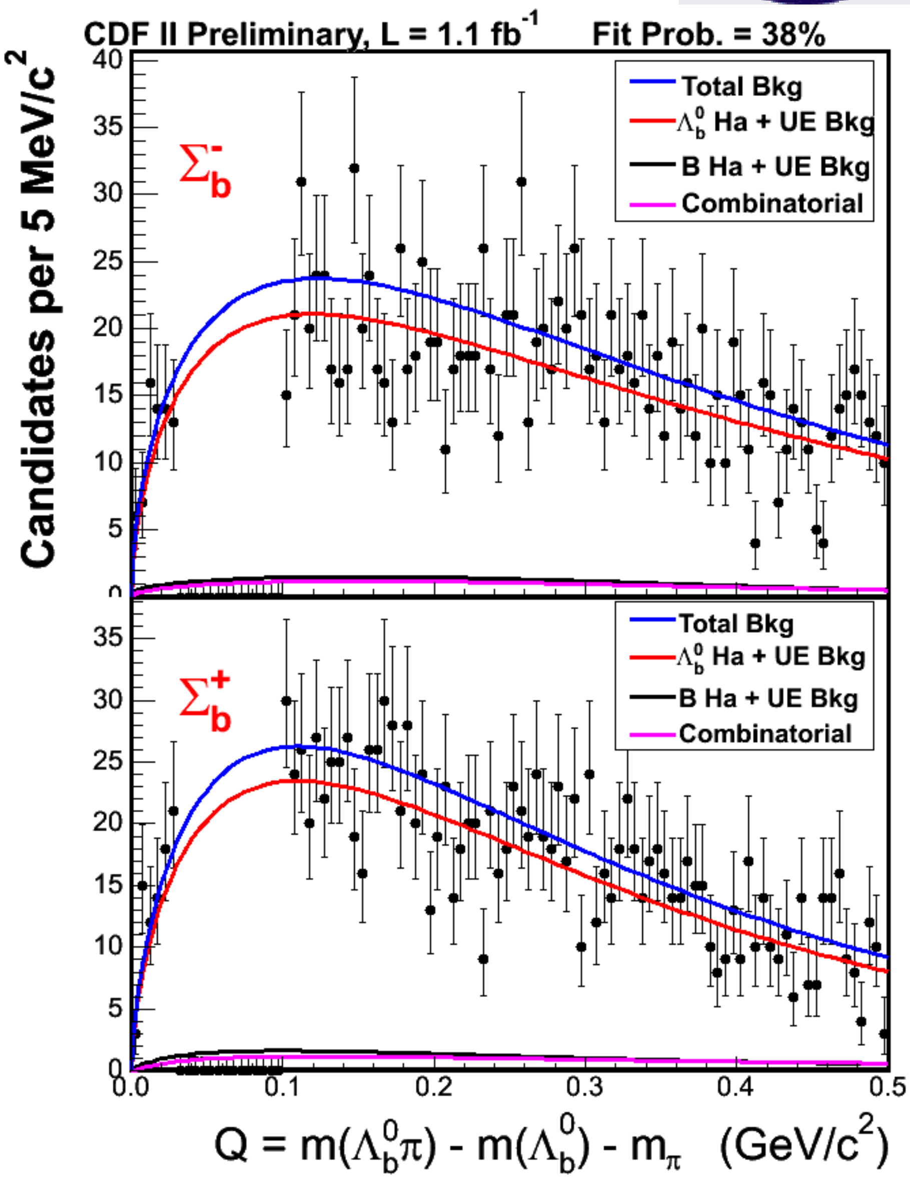




Proton from Λ_c and π from Λ_b usually satisfy two displaced track criteria

Σ_b Backgrounds

- Σ_b backgrounds:
  - Hadronization tracks around prompt Λ_b baryons – Dominant!
  - Hadronization tracks around *B* mesons reconstructed as Λ_b
  - Combinatorial background
- Determine background contributions from data and PYTHIA Monte Carlo
- Good agreement between Σ_b data and the expected background

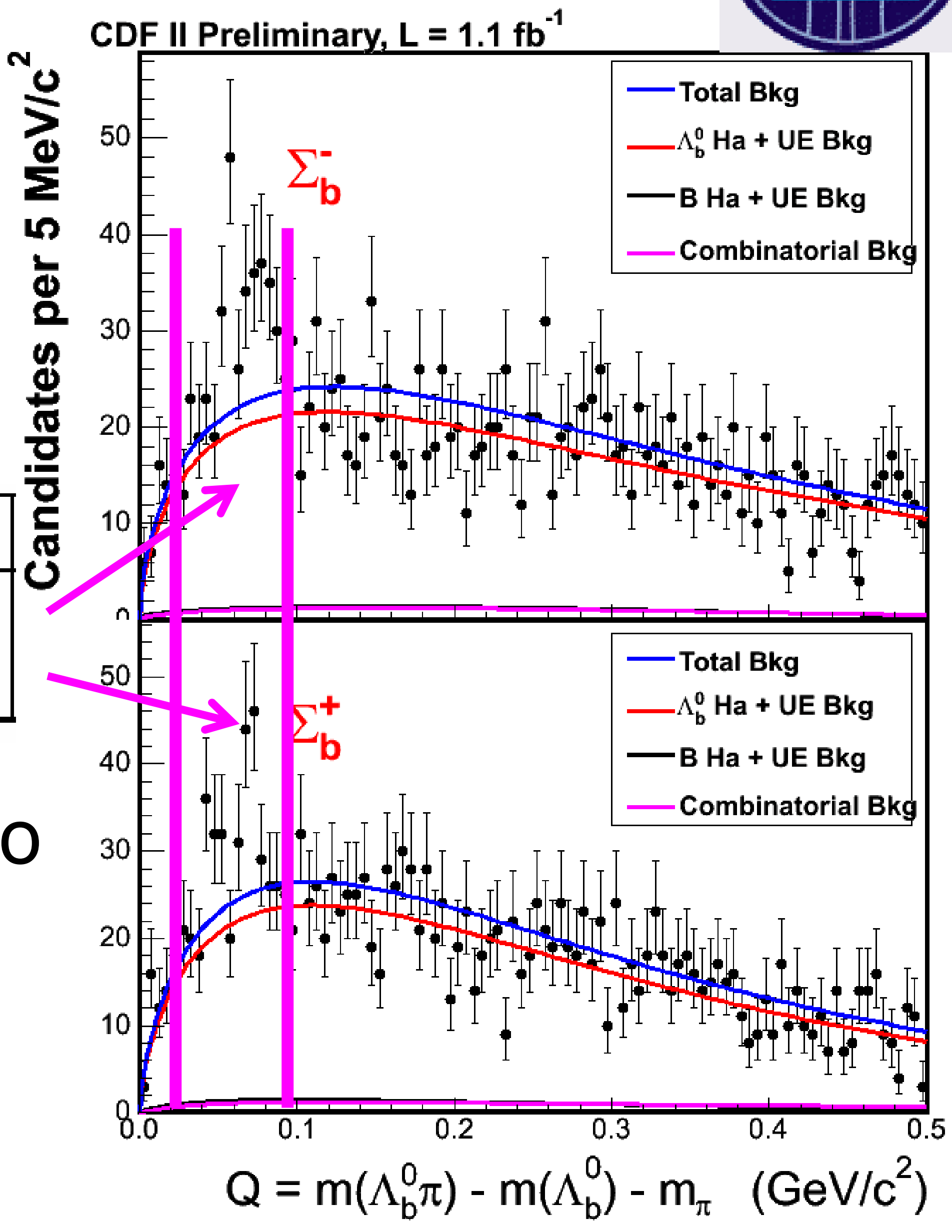


Σ_b Signal Region

- Excess observed in signal region:

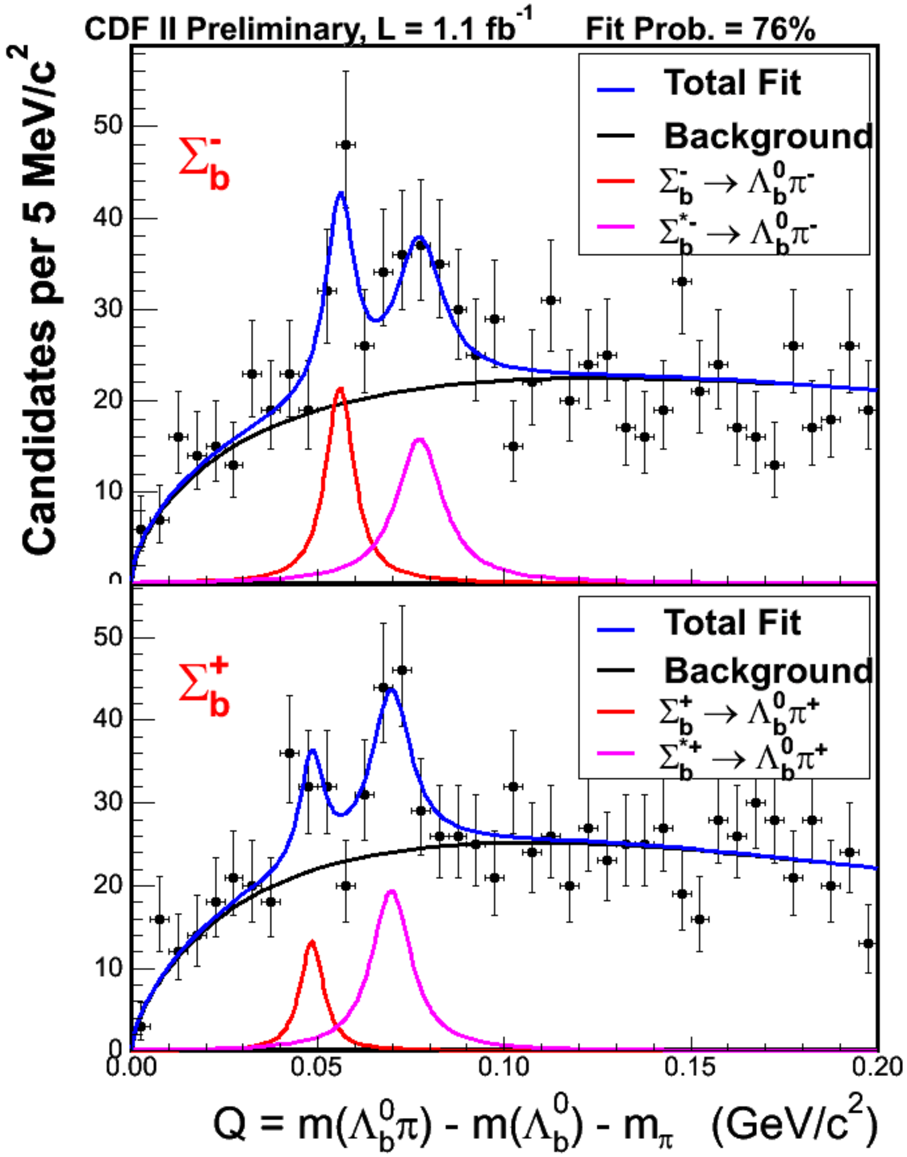
Sample	Data events	Bkg events
$\Lambda_b^0\pi^-$	406	288
$\Lambda_b^0\pi^+$	404	313

- Perform Σ_b signal fit to data



Σ_b Observation

- Model signal with unbinned likelihood fit
  - Background fixed
  - Peaks modeled by a Breit-Wigner convoluted with the detector resolution
  - Common parameter: $m(\Sigma_b^*) - m(\Sigma_b)$
- Observe signals consistent with lowest lying charged $\Sigma_b^{(*)}$ states
- No signal hypothesis excluded at high confidence level (> 5 σ)



Σ_b Measurement Results

$$m(\Sigma_b^+) - m(\Lambda_b^0) - m_\pi = 48.5^{+2.0}_{-2.2}\ (\text{stat.})\ ^{+0.2}_{-0.3}\ (\text{syst.})\ \text{MeV}/c^2$$

$$m(\Sigma_b^-) - m(\Lambda_b^0) - m_\pi = 55.9 \pm 1.0\ (\text{stat.})\ \pm 0.2\ (\text{syst.})\ \text{MeV}/c^2$$

$$m(\Sigma_b^{*-}) - m(\Sigma_b^-) = m(\Sigma_b^{*+}) - m(\Sigma_b^+) = 21.2^{+2.0}_{-1.9}\ (\text{stat.})\ ^{+0.4}_{-0.3}\ (\text{syst.})\ \text{MeV}/c^2$$

$$N(\Sigma_b^+) = 32^{+13}_{-12}\ (\text{stat.})\ ^{+5}_{-3}\ (\text{syst.})$$

$$N(\Sigma_b^-) = 59^{+15}_{-14}\ (\text{stat.})\ ^{+9}_{-4}\ (\text{syst.})$$

$$N(\Sigma_b^{*+}) = 77^{+17}_{-16}\ (\text{stat.})\ ^{+10}_{-6}\ (\text{syst.})$$

$$N(\Sigma_b^{*-}) = 69^{+18}_{-17}\ (\text{stat.})\ ^{+16}_{-5}\ (\text{syst.})$$

- Good agreement with theoretical predictions
- Theoretical models do well in non-perturbative QCD regime

Summary

- First observation of resonant $\Lambda_b\pi^{\pm}$ states
  - Consistent with lowest lying charged Σ_b states
  - With $m(\Lambda_b)$ = 5619.7 ± 1.2 (stat.) ± 1.2 (syst.) MeV/c^2,

$$m(\Sigma_b^+) = 5807.8^{+2.0}_{-2.2}\ (\text{stat.})\ \pm 1.7\ (\text{syst.})\ \text{MeV}/c^2$$

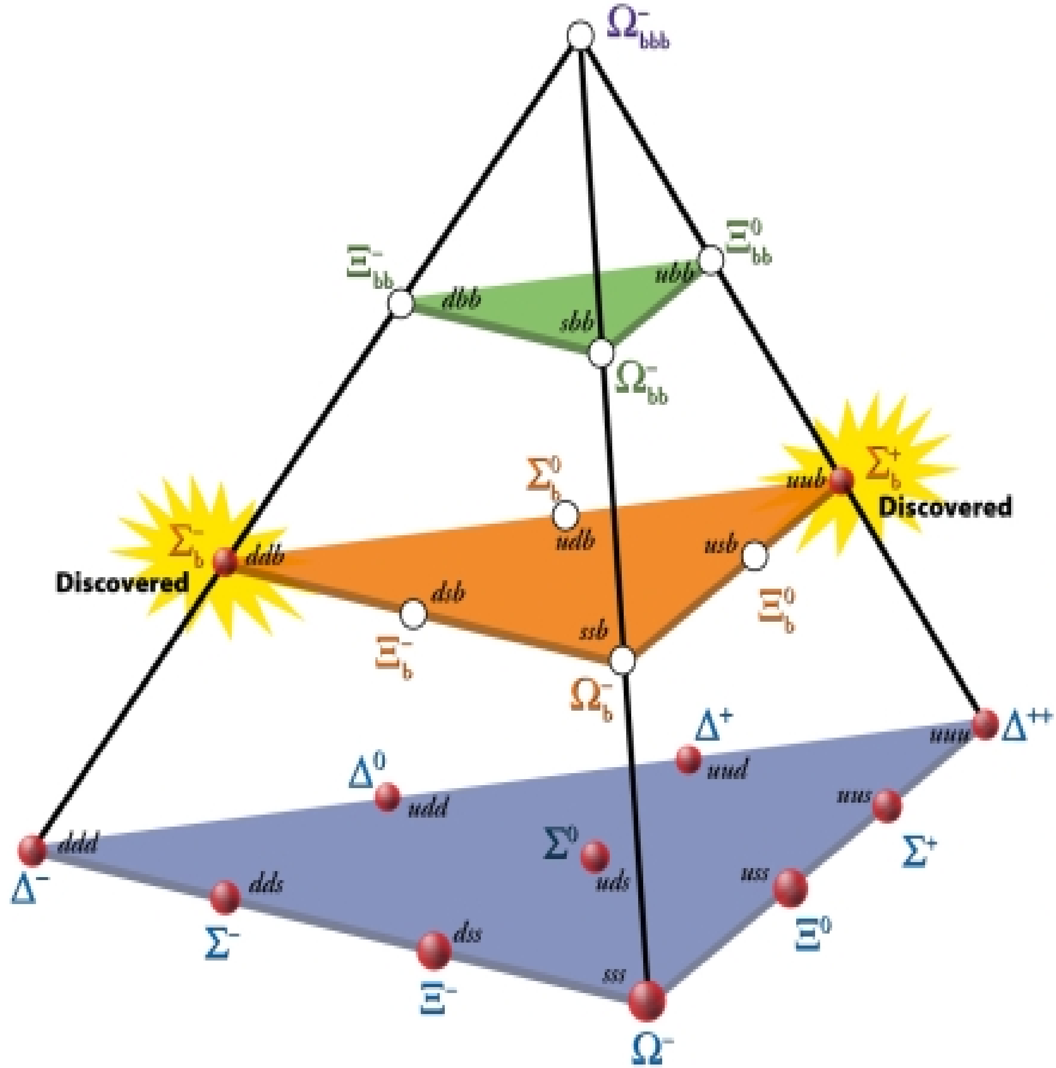
$$m(\Sigma_b^-) = 5815.2 \pm 1.0\ (\text{stat.})\ \pm 1.7\ (\text{syst.})\ \text{MeV}/c^2$$

$$m(\Sigma_b^{*+}) = 5829.0^{+1.6}_{-1.8}\ (\text{stat.})\ ^{+1.7}_{-1.8}\ (\text{syst.})\ \text{MeV}/c^2$$

$$m(\Sigma_b^{*-}) = 5836.4 \pm 2.0\ (\text{stat.})\ ^{+1.8}_{-1.7}\ (\text{syst.})\ \text{MeV}/c^2$$

- Continuing research:
  - Improve Σ_b measurement – measure width, polarization…
  - Search for *more* heavy baryons!
  - Continue testing theoretical models

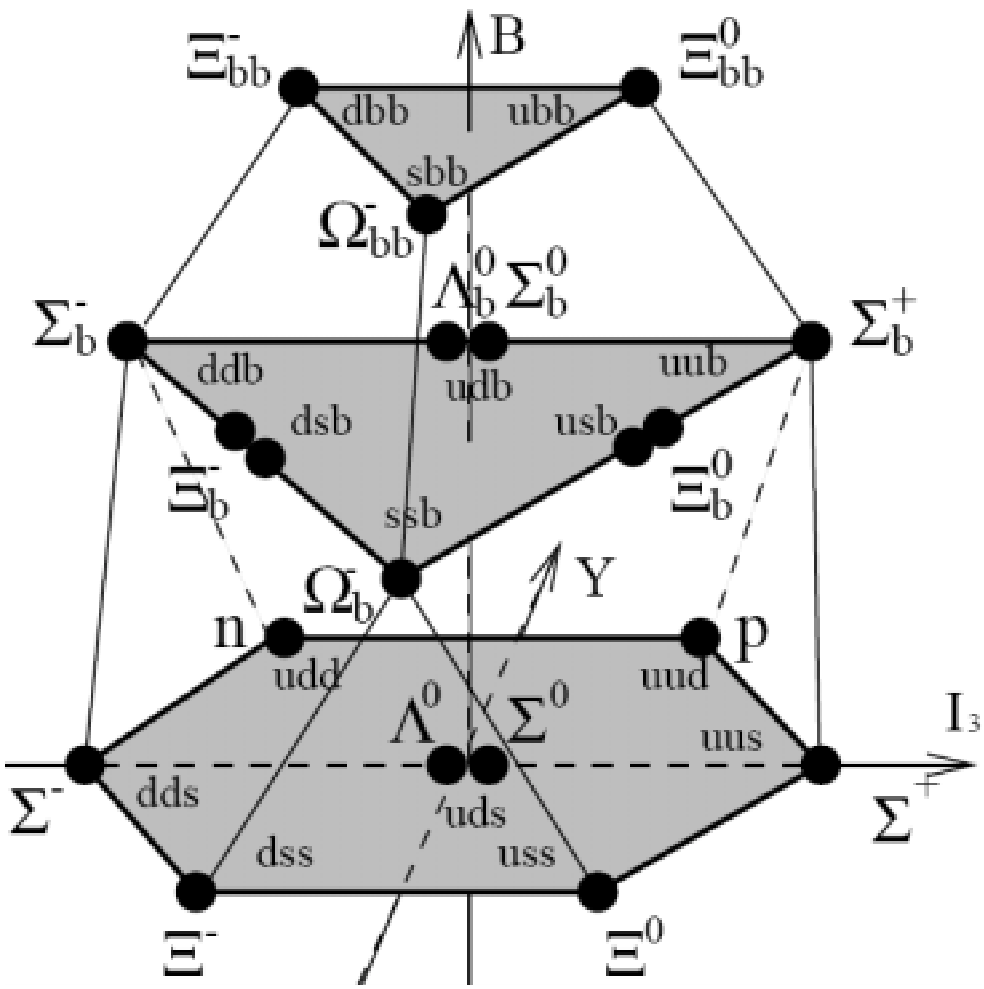
Σ_b Observation!



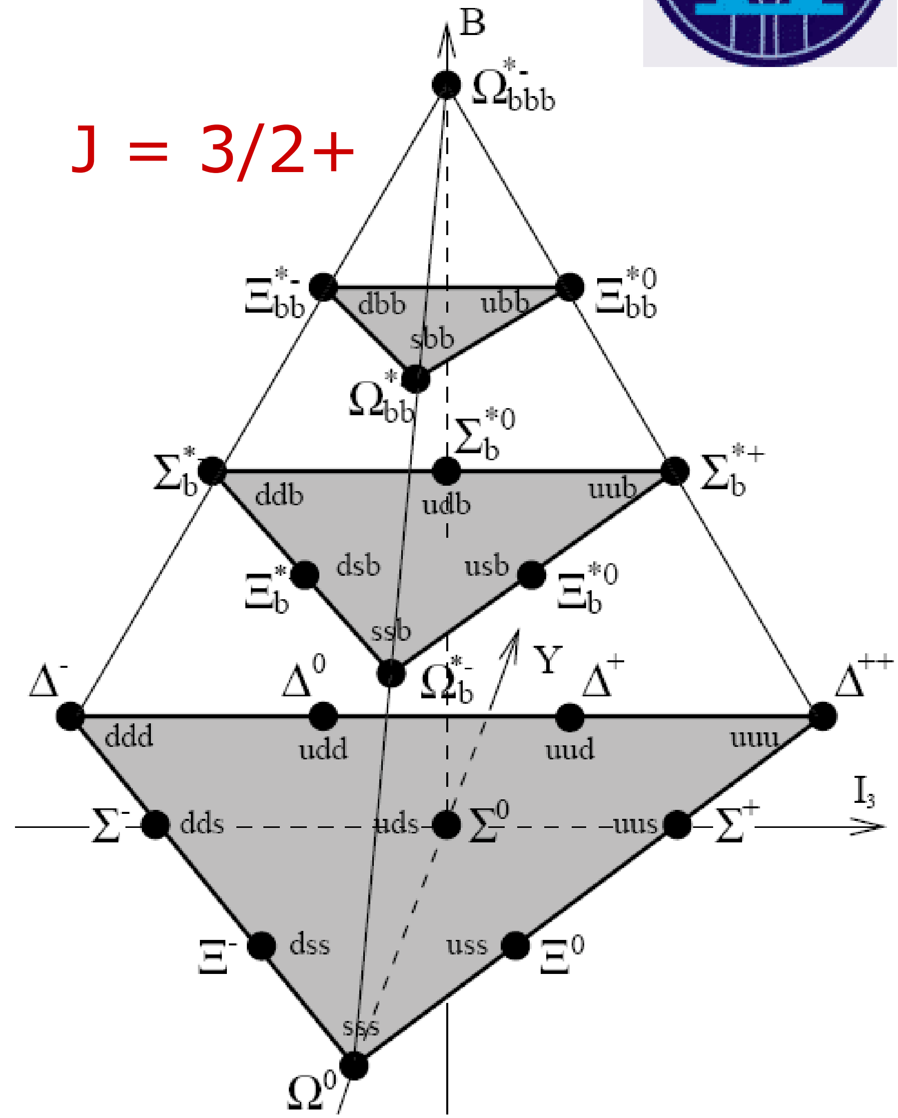
Backup Slides

Baryon multiplets:

J = 1/2+



J = 3/2+



Σ_b Backgrounds

- Σ_b backgrounds:
  - Hadronization tracks around prompt Λ_b – Dominant!
  - *B* meson hadronization tracks
  - Combinatorial background
- Take background shapes from data or PYTHIA Monte Carlo, normalize using Λ_b sample comp.
- Backgrounds are fixed before looking in the Σ_b signal region

Background type		Sample	Contribution
Λ_b HA+UE		PYTHIA	dominant
Combinatorial		Upper Λ_b sideband $m(\Lambda_b) \in [5.8, 7.0]$	small
B mesons		data	small
B meson reflections	*π_Σ from B HA+UE*	Pythia	Dominant within B
	π_Σ from B decay (D^*, D^{**})	Inclusive BGen	negligible
	π_Σ from B^{**}	B0 Pythia	negligible

Strength of Σ_b hypothesis

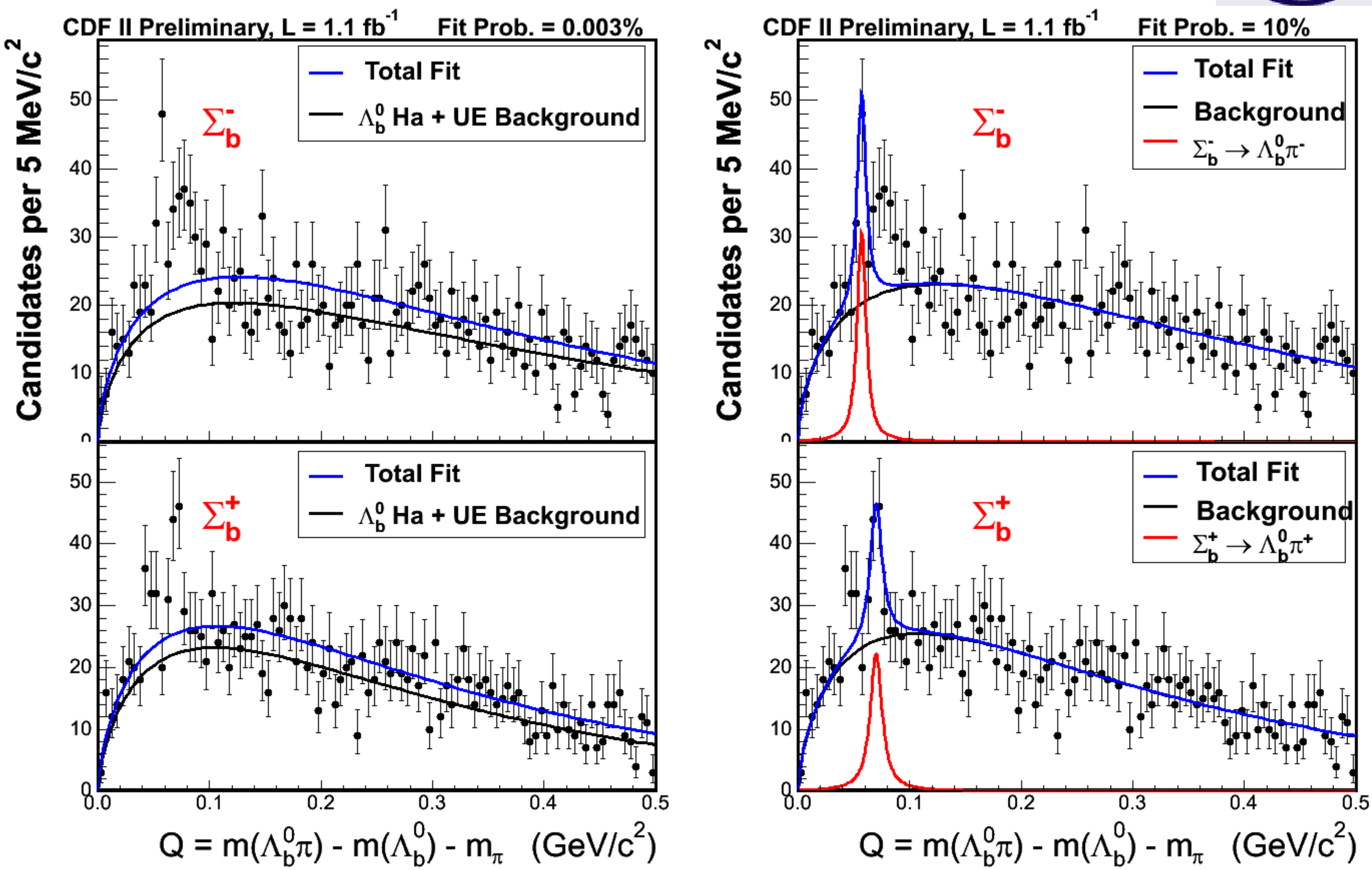
- Evaluate Likelihood Ratio:

$$LR = \frac{\mathcal{L}_{\text{no peak fit}}}{\mathcal{L}_{\text{four peak fit}}}$$

- Systematic variations included as nuisance parameters
- Simplistic MC studies show the no signal hypothesis excluded at > 5 σ level

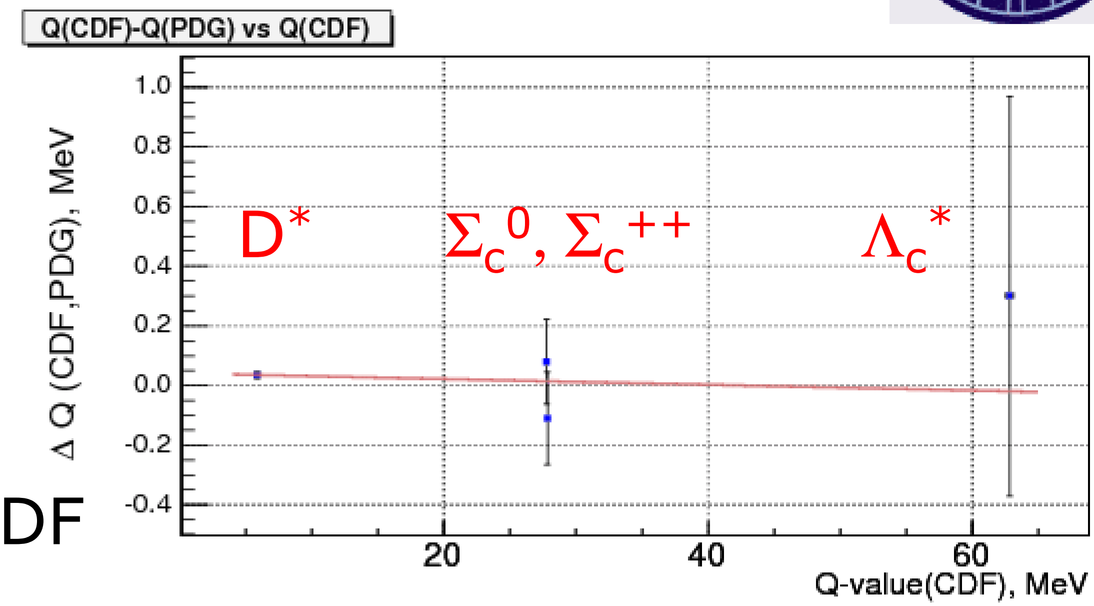
Hypothesis	$\Delta(-\ln \mathcal{L})$	*p*-values
No Signal	42.4	$< 8.3 \times 10^{-8}$ ($> 5.2\ \sigma$)
2 Σ_b States	15.3	9.2×10^{-5} ($3.7\ \sigma$)
No Σ_b^- Peak	11.7	3.2×10^{-4} ($3.4\ \sigma$)
No Σ_b^+ Peak	3.9	9.0×10^{-3} ($2.4\ \sigma$)
No Σ_b^{*-} Peak	10.8	6.4×10^{-4} ($3.2\ \sigma$)
No Σ_b^{*+} Peak	11.3	6.0×10^{-4} ($3.2\ \sigma$)

Zero and Two Peak Fits



Systematics

- Two sources of systematics:
  - Mass scale
  - Assumptions made in the fit to data
- For mass scale: take difference between CDF and PDG values for
  - D^*, Σ_c^0, Σ_c^{++}, and Λ_c^*
  - Model with a linear function to extrapolate for Σ_b Q values
  - This is the largest syst error on the mass diff measurement!



Particle	Q (MeV/c^2)	Mass Syst. (MeV/c^2)
Σ_b^+	48.2	0.19
Σ_b^-	55.9	0.22
Σ_b^{*+}	69.7	0.28
Σ_b^{*-}	77.4	0.32
$\Sigma_b^* - \Sigma_b$	$\Delta Q = 21.2$	0.10

Fit Systematics

- Background model
  - Limited knowledge of Λ_b had. shape (reweighting Pythia) – largest error on the yield measurements
  - Sample composition from Λ_b mass fit
- Signal model
  - Detector resolution underestimated in Monte Carlo
  - Natural width estimation has some uncertainty
  - Constraint that $m(\Sigma_b^{*-}) - m(\Sigma_b^{-}) = m(\Sigma_b^{*+}) - m(\Sigma_b^{+})$
- To evaluate:
  - Generate Toy MC samples with one systematic variation
  - Fit samples with variation and default fit
  - Take the average shift in parameter value as syst. error
- All systematics much smaller than statistical error!

Σ_b Systematics

Parameter	Mass scale	Λ_b Sample Comp.	Λ_b Ha+UE Norm.	Λ_b Ha+UE Shape	Λ_b Ha+UE Reweight	Det. Reso.	Σ_b Nat. Width	Σ_b^*-Σ_b Isospin Diff.	Total
Σ_b^- Q (MeV/c^2)	0.22 -0.22	0.00 -0.03	0.009 -0.002	0.000 -0.011	0.04 -0.0004	0.0 -0.011	0.009 -0.005	0.06 0.0	0.23 -0.22
Σ_b^+ Q (MeV/c^2)	0.19 -0.19	0.03 0.0	0.013 -0.013	0.013 0.0	0.0 -0.11	0.0 -0.014	0.01 -0.02	0.0 -0.11	0.19 -0.25
Σ_b^*-Σ_b Q (MeV/c^2)	0.10 -0.10	0.05 0.0	0.14 -0.13	0.04 0.0	0.32 0.0	0.02 0.0	0.07 -0.07	0.0 -0.26	0.38 -0.32
Σ_b^- events	0.0 0.0	0.7 0.0	2.2 -2.2	0.3 0.0	7.4 0.0	0.3 0.0	3.4 -3.4	0.0 -0.08	8.5 -4.1
Σ_b^+ events	0.0 0.0	3.3 0.0	2.1 -2.1	1.2 0.0	2.3 -1.8	0.3 0.0	1.8 -2.0	0.0 -0.004	5.0 -3.4
Σ_b^{*-} events	0.0 0.0	0.4 0.0	4.8 -4.7	0.3 0.0	14.7 0.0	0.1 0.0	1.7 -1.7	0.0 -0.16	15.6 -5.0
Σ_b^{*+} events	0.0 0.0	7.3 0.0	4.8 -4.8	2.8 0.0	4.6 -2.9	0.2 0.0	0.8 -0.8	0.16 0.0	10.3 -5.7

- Mass scale systematic dominates
- All systematics much smaller than statistical error!